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EXPLOSIBILITY TESTS ON FERROSILICON DUST

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Canadian Explosive Atmospheres Laboratory

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EXPLOSIBILITY TESTS ON FERROSILICON DUST

by

K.C. Cheng * and D. Cox **

ABSTRACT

The ignition and explosion characteristics of ferrosilicon dusts were investigated with a 1.23 L Hartmann apparatus. Various size fractions were tested for the dust explosibility and explosion pressure. The 'up-and-down' method was used to determine the minimum explosive concentration of the dispersed dust clouds. The pressure developed from each dust explosion was detected by a piezoelectric transducer and recorded with a digital oscilloscope in a form of pressure-time curve from which the maximum explosion pressure and the rate of pressure rise were determined. The results are presented in fifteen figures and twelve tables.

The results indicate that fine ferrosilicon dusts are more easily ignited and pose a greater explosion hazard than the coarse dusts. The minimum explosive concentration for the -37, -44, -74 and -840 μm ferrosilicon dusts is 165, 186, 284 and 318g/m^3, respectively. The maximum explosion pressure, for the -30, -44, -74 and -840 μm ferrosilicon is 686, 600, 342 and 400 kPa, and the maximum rate of pressure rise for the same particle fractions is 42.0, 20.6, 3.0 and 3.4 MPa/s, respectively. The reduction of particle size has a greater influence on the rate of pressure rise than on the explosion pressure.

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Keywords: Dust explosion, ferrosilicon, metal powders, explosibility, ignitability, explosion pressure, rate of pressure rise.

ESSAIS D'EXPLOSIBILITÉ CONDUITS SUR DES POUSSIÈRES DE FERROSILICUM

par

K.C. Cheng * et D. Cox **

RÉSUMÉ

On a étudié avec un appareil de Hartmann de capacité 1,23 L les caractéristiques d'inflammation et d'explosion des poussières de ferrosilicium. On a soumis diverses fractions granulométriques à des essais d'explosibilité et à des mesures de la pression à l'explosion. On a employé la méthode "montante et descendante" pour déterminer la concentration minimale à l'explosion du nuage de poussières dispersées. On a décelé la pression créée par chaque coup de poussières avec un transducteur piézoélectrique et on l'a enregistrée avec un oscilloscope numérique, qui a donné un graphique pression-temps à partir duquel on a déterminé la pression maximum à l'explosion et la vitesse d'accroissement de la pression. On a présenté les résultats dans quinze figures et douze tableaux.

Les résultats indiquent que les fines poussières de ferrosilicium s'enflamment plus facilement et présentent un plus sérieux danger d'explosion que les poussières plus grosses. Les concentrations minimales à l'explosion des poussières de ferrosilicium de dimensions -37, -44, -74 et -840 µm, sont de 165, 186, 284 et 318g/m³, respectivement. Dans le cas des poussières de ferrosilicium de -30, -44, -74 and -840 µm, les pressions maximales à l'explosion sont respectivement 686, 600, 342 et 400 KPa respectivement, et les vitesses maximales d'accroissement de la pression 42,0; 20,6; 3,0 et 3,4 MPa/s. La diminution de la granulométrie a une plus grande influence sur la vitesse d'accroissement de la pression que sur la pression à l'explosion.

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Mots-clés: Coup de poussières, poussières de ferrosicilium, concentration minimale à l'explosion, pression à l'explosion, vitesse maximale d'accroissement de la pression.

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INTRODUCTION

A dust explosion, involving ferrosilicon dusts generated in a ball mill, occurred at the magnesium-calcium plant of the Chromasco Operation at Haley, Ontario. The Ontario Ministry of Labour asked the Mining Research Laboratories, CANMET, Energy, Mines and Resources Canada for a laboratory study on the ignition and explosion characteristics of this mill-grade ferrosilicon.

Finely-ground ferrosilicon is used as a reducing agent in the Pidgeon Ferrosilicon Process for the production of magnesium. The ferrosilicon is made from silica sand, coke and scrap iron in an arc furnace and then consolidated into a matte form by molding. The solid ferrosilicon is then reduced to a fine powder by a crusher and a ball mill before it is mixed with the fine calcined dolomite and fluorspar for briquetting. The briquettes are retorted for crystalline magnesium in reduction furnaces. The main location of concern is the ball mill where the airborne ferrosilicon is confined and is susceptible to a dust explosion hazard in conjunction with the possible generation of hydrogen gas.

A dust explosion is characterized by rapid combustion of dust clouds and a relatively rapid development of pressure in a confined or partially confined space. To cause a dust explosion, the dust concentration must be within lower and upper explosive limits, and the magnitude of ignition source must be greater than the minimum ignition energy for that material. The minimum ignition energy is the least amount of heat energy that is required to produce a hot spot or flame for the initiation and propagation of a dust explosion. Depending on the composition and the particle size distribution of the ferrosilicon dusts, it was reported that the ignition and explosion characteristics may vary largely (1).

Equipment similar to that developed by I. Hartmann group of the U.S.B.M. has been used for the measurements of minimum explosive concentration, the maximum explosion pressure and the rate of pressure rise (2). The "up-and-down" method developed by W.J. Dixon is used for the evaluation of minimum explosive concentration for the dust clouds (3). The minimum explosive concentration in nominal concentration, g/m^3 representing the lower explosive

limit is used as an indicator to characterize the ignitability or sensitivity of a combustible material to a dust explosion. The destructive power or the severity of a dust explosion is assessed by the maximum pressure and the rate of pressure rise. A piezoelectric pressure transducer was used in this work to measure the explosion pressure. The pressure-time profile developed by a dust explosion was recorded with a digital oscilloscope. The lycopodium powder was used as a reference material as recommended by the ASTM for the calibration of equipment (4), and the test results are compared with those obtained by other laboratories (5-7).

SAMPLE PREPARATION

The head sample was collected at the discharge side of the ball mill, representing the end product of size reduction for the ferrosilicon at Chromasco. The sample was screened with Tyler sieves for various size fractions and the result is shown in Table 1. Each fraction was tested separately for the minimum explosive concentration, the maximum explosion pressure and the rate of pressure rise. The dust particles greater than 20 mesh (+840 μm) size were difficult to disperse in the air and were excluded for the explosion test. The minus 20 mesh size sample is considered as the "as received" dust sample that represented the in-situ particle size distribution of a dust cloud in the ball mill or at the dust collecting facilities. The minus 200 mesh (74 μm) size sample is considered as the "standard sample" for dust explosibility tests in the laboratories.

Table 1 - Sieve Analysis For Ferrosilicon Dust Sample

		% weight of particle size distribution at various sieve ranges (mesh/μm)							
Sample	Total weight	+20	+100	+200	+270	+325	+400	+500*	-500
(mesh)	(g)	840	149	74	53	44	37	30	-30
Head	45	0.9	5.7	8.5	11.5	9.9	10.9	22.3	30.3
-20	45		10.0	9.9	9.0	11.3	8.5	22.8	28.5
-200	50				13.0	14.4	9.3	25.2	38.1
-325	30						34.8	29.4	35.8
-400	25							49.0	51.0

*This signifies for example, a particle size fraction between 400 and 500 mesh.

Before an explosion test was begun, the moisture content in the ferrosilicon was determined by taking several 5 g portions of the minus 20 mesh samples and drying in the oven at 75-80°C for a 20 to 24 h period. The result showed that all samples contain less than 0.5 % moisture. It is recommended that samples with more than 5% moisture should be dried before testing and that samples with less than 5% moisture should also be dried if difficulty in dispersing the dust sample is observed (4).

At the end of the laboratory work, the samples that remained in the glass jars were checked again for moisture using the same procedure. It was found that the moisture contents had increased to about 6%. However, no problem in dispersing the ferrosilicon dust sample was encountered during the eight weeks test period and the dust particles in the glass jars had been stayed free and unclustered.

A chemical analysis of the composition of ferrosilicon is shown in Table 2. The silicon percentage could only be determined approximately due to the accuracy of the analytical method used for high silicon concentration. In addition, the scrap iron used for making ferrosilicon contains impurities. Other analyses have shown the presence of aluminum, phosphorus and arsenic.

Table 2 - Chemical analysis of ferrosilicon

Composition	-200 mesh sample	-325 mesh sample
	%	%
Iron	10.3	9.2
Silicon	77.7	83.0
Others	undertermined	

MINIMUM EXPLOSIVE CONCENTRATION

EQUIPMENT AND TEST PROCEDURE

The 1.23 L Hartmann apparatus, as shown in Figure 1 (without th use of pressure measuring system) in conjunction with a 1.31 L air-dispersion tank, was used for the tests to determine the minimum explosive concentrations for the dust samples. The combustion tube, made of steel pipe, is 30.5 cm long and 7.0 cm in internal diameter. The tube sits vertically on the base and is anchored by 4 hinged bolts. A filter paper covers the top of the tube and is held in place by a locking ring. The electrodes are mounted inside the tube and are located at about 11 cm above the dispersion cup. The air gap between the electrodes is set at 4.8 mm. An AC induction spark is used as the ignition source with a rated spark current of 23 mA and a voltage of 10 kV at the output of the transformer.

To conduct a test, a weighed amount of dust sample is spread uniformly around the dispersion cup of the base unit. Then the tube is bolted in place and a new filter paper is placed on top of the tube and held in place by a locking ring. A pencil is used to punch a 1.5 mm hole in the center of the filter paper for the release of air pressure during a dust dispersion.

The air dispersion tank is charged with the compressed air from an air cylinder to a 103 kPa (15 psig) gauge pressure while the solenoid valve that isolates the combustion tube and the air tank is closed. The arc-air delay switch is set on the 100 ms position for air delay, to ensure that the arc comes on first before the sample is dispersed. Then, the dust sample is dispersed into a cloud by activating the ignition switch that controls the arc and the solenoid valve. When the test produces an explosion, combustion products are formed and the pressure developed bursts the filter paper resulting in a sharp loud bang. When a test does not result in an explosion, the unruptured filter paper must be discarded and a new test performed.

The 'up-and-down' method is used for the determination of minimum explosive concentration. The results of a complete test are given in Table 3 as an example. A prerequisite condition for using this method is that the test results must exhibit normal or log-normal distribution and the test levels must be equally spaced.

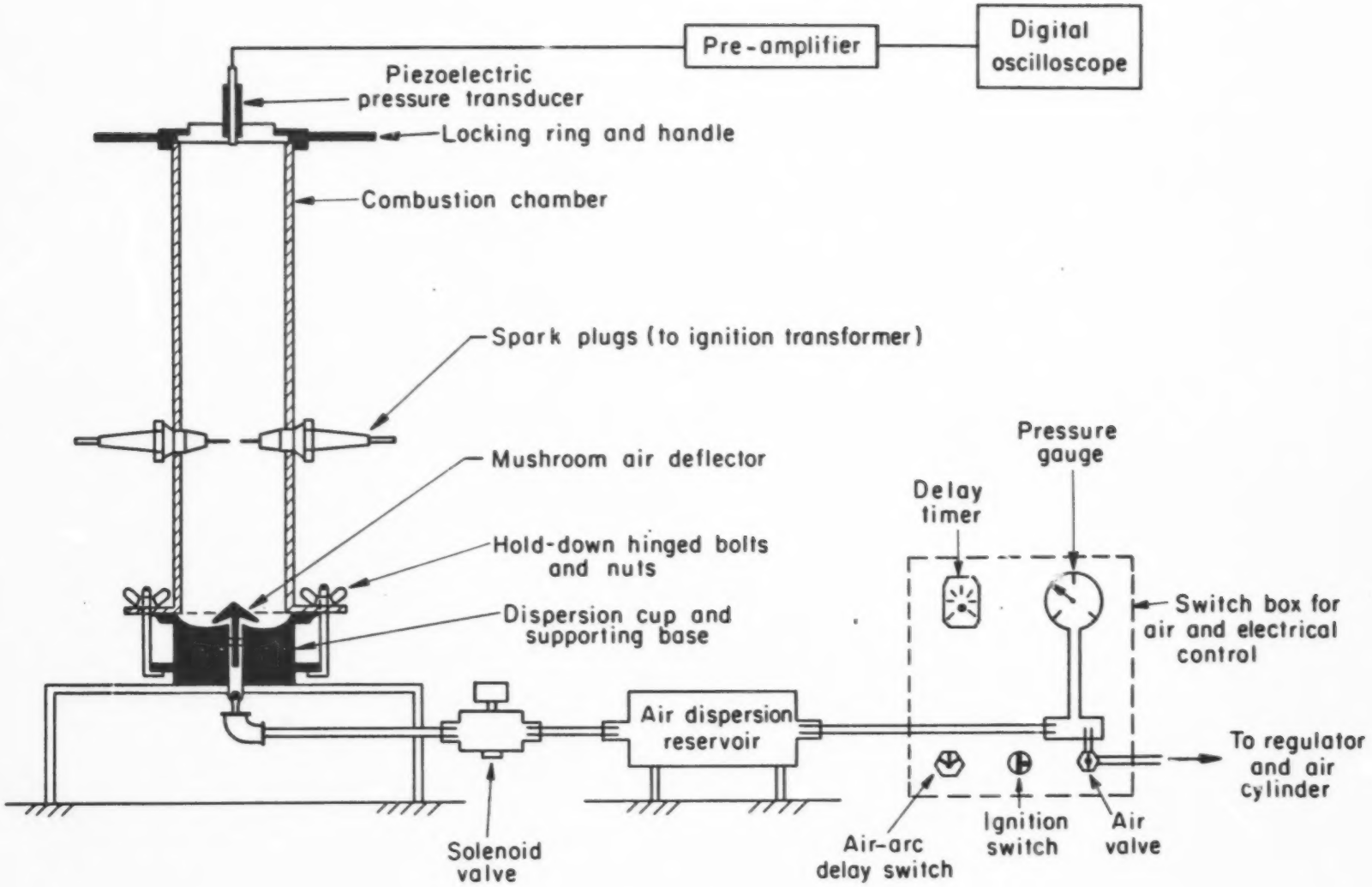

Fig. 1 - Schematic of apparatus for dust explosion pressure tests

Table 3 - Result of 'up-and-down' test for -200 mesh ferrosilicon

Sample weight (mg)	Normalized weight (log)	Sequence of test	No. of tests X	No. of tests 0
281.2	2.449			
309.0	2.490	9 0 23 0 25 0 26 0 27 0 29 0 34 0 39 0 43 0		7
339.6	2.531	2 0 3 0 4 X 5 0 7 0 15 0 16 0 17 0 18 X 20 X 22 X 24 X 28 0 31 X 33 0 35 0 36 0 37 X 38 0	7	11
373.3	2.572	1 X 2 X 3 X 6 X 8 0 10 X 12 X 13 X 14 X 19 X 21 X 30 0 32 X 34 X 36 X 37 X	12	3
410.2	2.613	2 X 11 X 31 X	3	
450.8	2.654			
(Spacing d = 0.041)		Total	22	21

Analysis based on failure (O's) and d = +0.041

	n_i	y_i	$n_i y_i$	$n_i y_i^2$
	7	2.490	17.430	43.40070
	11	2.531	27.841	70.46557
	3	2.572	7.716	19.84555
Total (Σ)	21		52.987	133.71182
Notation	N		A	B

Testing is started by choosing an initial sample weight near the anticipated mean. If the first test produces an explosion, the weight for the second test is decreased by one level. If it does not explode, the weight is increased by one level. An explosion is represented by "X" and a failure, by "0".

As the test continues, a new sample is normally tested at the level immediately above or below the previous test level, depending on whether the previous test was an explosion or a failure. This method is very effective in estimating the mean ($\overline{X}$), i.e., the 50% chance of explosibility (P_{50}), or the so-called minimum explosive concentration. It is not, however, a good method for the estimation of small or large percentiles at the extreme tailed ends of a log-normal distribution, such as the estimate of dust explosion probability at less than 5% or more than 95% ranges. Up-and-down tests also provide rough estimates for the dust explosibility in the 5-10% and 90-95% ranges. The equations and notations used for the calculation of explosive dust concentration are defined and listed in Appendix A.

To analyze the up-and-down test results, either the outcome of explosions or the outcome of failures is used, depending on which has the smaller total. Table 3 shows that the analysis is based on the outcome of failures because there are fewer failures than successes. The value 'd' in Eq 3 is positive when the analysis is based on the failures, and negative when it is based on the explosions. The symbol 'd' is the step size in log value between the testing levels. It should be approximately equal to one standard deviation, or within the range of 0.5 to 2.0, as specified in Eq 11. Using the test results of Table 3, Appendix B illustrates the application of the formulae in Appendix A, and a pocket calculator can be used for the determination of minimum explosive concentration. Also, a program has been written in BASIC which can be run on a Peach microcomputer to evaluate the data from the up-and-down tests. Tables 4 and 5 provide summaries of test results for ferrosilicon, lycopodium and Pittsburgh coal dusts.

Table 4 - Determination of explosive dust concentration for ferrosilicon by the 'up-and-down' method

Particle size	Test levels	No. of tests		S_y^2/D^2	D/S	S	10% explosibility	50% explosibility
		Explosion	Failure					
(mesh)	g/m^3	(X)	(O)			(log)	g/m^3	g/m^3
-20	276-367	22	22	0.43	1.34	0.0307	280	307
	251-367	22	21	0.53	1.10	0.0374	268	299
	276-446	19	19	1.16	0.52	0.0802	275	349
-200	251-334	22	21	0.46	1.26	0.0326	258	284
-325	157-208	19	20	0.56	1.05	0.0392	166	186
-400	143-189	19	20	0.56	1.06	0.0388	146	164
	143-208	21	20	0.54	1.09	0.0376	151	169
-500	130-208	21	22	1.26	0.48	0.0857	125	161
	143-189	30	30	0.69	0.87	0.0474	144	165
270-325	304-1035	0	16	No explosion up to 1035 g/m^3				
325-400	251-334	20	21	0.20	2.70	0.0152	279	292
	309-468	21	18	2.02	0.30	0.0994	286	383
400-500	157-229	21	22	0.79	0.75	0.0544	170	200

Table 5 - Determination of explosive dust concentration for lycopodium and Pittsburgh coal by the 'up-and-down' method

Test levels	No. of tests: Explosion	No. of tests: Failure	S_y^2/D^2	D/S	S	5% explosibility	10% explosibility	50% explosibility
g/m³	(X)	(O)			(log)	g/m³	g/m³	g/m³
(i) Lycopodium-tested with dust dispersion technique (A):								
25.4-45.0	22	21	0.333	1.70	0.0487	26.4	27.4	31.7
21.0-37.2	21	20	0.385	1.49	0.0553	23.5	24.6	29.0
25.4-45.0	22	21	0.362	1.58	0.0525	25.3	26.4	30.8
23.1-30.7	20	20	0.471	1.24	0.0336	24.7	25.4	28.0
25.4-45.0	22	21	0.362	1.58	0.0526	25.1	26.2	30.6
25.4-40.9	22	21	0.862	0.69	0.0750	24.3	25.9	32.3
(ii) Lycopodium-tested with dust dispersion technique (B):								
17.7-28.6	18	17	0.883	0.68	0.0768	17.0	18.1	22.7
(iii) Pittsburgh coal-tested with dust dispersion technique (A):								
80-117	21	20	0.358	1.60	0.0520	77.8	81.3	94.8
66-117	22	21	0.348	1.64	0.0506	78.0	81.4	94.5
88-113	22	21	0.448	1.29	0.0270	87.3	89.3	96.7

RESULTS AND DISCUSSION

Table 4 shows a summary of up-and-down test results for various size fractions of the ferrosilicon dust samples. Most tests meet the criteria of S_y^2/d^2 greater than 0.3 and d/S between 0.5 and 2.0 except the test for the 325-400 mesh fraction. The minimum explosive concentration or 50% explosibility for the -37, -44, -74 and -840 μm ferrosilicon is 165, 186, 284 and 318 g/m³, respectively. These results indicate that fine dusts are more easily ignited

and, therefore, pose a greater explosion hazard than coarse dusts. This is due to that the smaller particles have more surface area per unit weight for reaction. The current ignition system used for the Hartmann apparatus is unable to initiate an explosion for the 270-325 mesh ferrosilicon particles although it is possible that a stronger ignition source would initiate an explosion. The 10% explosibility represents the estimate of dust concentration at which an explosion may occur once in ten trials.

Table 5 shows a summary of the up-and-down test results for the reference materials, lycopodium powder and standard Pittsburgh coal. The lycopodium is considered as a major reference material because it has a uniform shape and a relatively uniform mean particle size of about 29 μm. The calibration tests for these materials were performed at intervals throughout the period of testing.

The dust dispersion techniques in reference (2) are designated (A) for the test of minimum explosive concentration (MEC) and (B) for the test of explosion pressure. Technique (A) is applied by using the 103 kPa (15 psig)* compressed air in a 1.31 L dispersion tank and technique (B), the 690 kPa (100 psig) compressed air in a 50 c.c. cylinder. The MEC for lycopodium powder was determined to vary from 28 to 32 g/m^3 and for the -200 mesh Pittsburgh coal, from 94 to 97 g/m^3. The Pittsburgh coal sample used for the tests was prepared in 1982 and the minimum explosive concentration determined at that time ranged from 60 to 85 g/m^3 throughout the year. The tests recorded in Table 5 show that the minimum explosive concentration for the lycopodium powder is 22.7 g/m^3 about 25% less by using the dust dispersion technique (B), relative to technique (A). It is evident that the air dispersion system is one of the important factors that affect the test results. The type used should be specified particularly when the results are to be compared with others.

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*Note: 1 psi = 6.895 kPa.

The results of Tables 4 and 5 are plotted in Fig. 2. This figure shows that the minimum explosive dust concentration reduces significantly as the particle size reduces, suggesting that dust concentrations greater than 100 g/m^3 may be explosible for the finer range of dusts.

In this connection, it is noteworthy that the narrow-size range sample of ferrosilicon (between 400 and 500 mesh) resulted in a slightly higher 50% explosion probability concentration than the "less than" size characteristic curve. This is to be expected because the narrow-range sample contained fewer smaller particles than the "less than" sample and was therefore more explosion-prone.

Note that the result of coarse -20 mesh FeSi in Table 4 is not plotted in Fig. 2, because a greatly extended horizontal scale would have been required. The -20 mesh smaple closely corresponds to the sample gathered at the mill discharge. The average 50% explosibility concentration for this sample is 318 g/m^3 with an approximate variation of 10%. Evidently, the 50% explosibility curve does not continue to rise with particle size at the slope shown in the figure, but rather levels off at increased sizes.

Two other data points are plotted in Fig. 2. These show the relationship of minimum explosive concentration for two 'standard' materials-Pittsburgh coal and lycopodium dust to ferrosilicon. These exhibit minimum concentration values varying from one third to one fifth of the ferrosilicon values for corresponding sizes. This confirms in part the United States Bureau of Mines classification of ferrosilicon as weak explosive material in reference (1) for the -200 mesh size samples.

EXPLOSION PRESSURE AND RATES OF PRESSURE RISE

EQUIPMENT AND TEST PROCEDURE

The equipment and test procedures used for the determination of explosion pressure and rates of pressure rise are specified in (2 and 4). Figure 1 is a schematic of the apparatus also used for the dust explosion

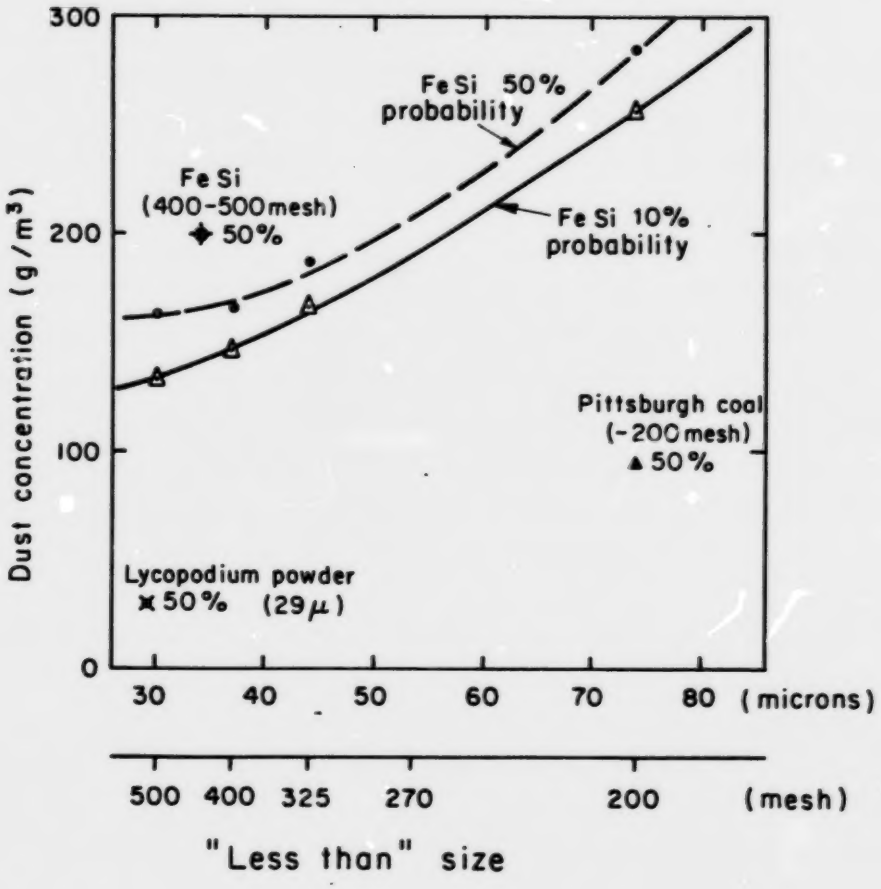

Fig. 2 - Minimum explosive dust concentrations for ferrosilicon

pressure tests. To start each test, a dust cloud is formed in a closed steel chamber with a jet of compressed air and ignited with a continuous AC electric arc. The pressure developed by the dust explosion is detected with a PCB-1679 piezoelectric transducer and recorded on a Nicolet programmable digital oscilloscope, from which the maximum pressure and rate of pressure rise are determined. For pressure tests, the dust sample is dispersed by releasing the compressed air from a 50 c.c. reservoir at 690 kPa, instead of from a 1.31 L reservoir at 103 kPa as described previously for the minimum explosive concentration tests. With a 50 c.c. reservoir and 690 kPa compressed air, the maximum pressure that can be developed in the explosion chamber from the dispersion air alone, is (64 ± 3.5) kPa after the solenoid valve is opened for 200 to 300 ms. The pressure of dispersing air at the time of ignition is generally between 20 and 55 kPa depending on the dust concentration and the ignitability of the test materials.

A pressure-time profile from a dust explosion is shown in Fig. 3. The maximum pressure (P_1) and the average rate(P_1/t_1) and the maximum rate $(dP_1/dt)_{max}$ of the pressure rise are calculated from the pressure-time curve using the Nicolet oscilloscope. The ignition delay (Δt_o) is defined as the time interval that is required for the ignition of a dust cloud after the dust is dispersed in the combustion chamber. A longer ignition delay indicates that more energy is required for the initiation of a dust explosion. To calculate the maximum pressure, the dispersing air pressure (ΔP_o) is subtracted from the peak pressure. The average rate of pressure rise is the maximum pressure divided by the time interval between the ignition point and the occurrence of maximum pressure. The maximum rate of pressure rise is the steepest slope on the pressure-time curve. The tests for various size fractions of ferrosilicon dusts were made at concentrations of 150, 250, 500, 750, 1000, 1500, 2000 and 3000 g/m³. Lycopodium powder was used as a reference material and tested at various concentration levels from 25 to 3000 g/m³ for obtaining the reference values of the maximum explosion pressure and the maximum rate of pressure rise.

RESULTS AND DISCUSSION

Figures 4A and 4B show some of the pressure-time curves for dust explosions that were tested with -500 mesh ferrosilicon at concentrations of

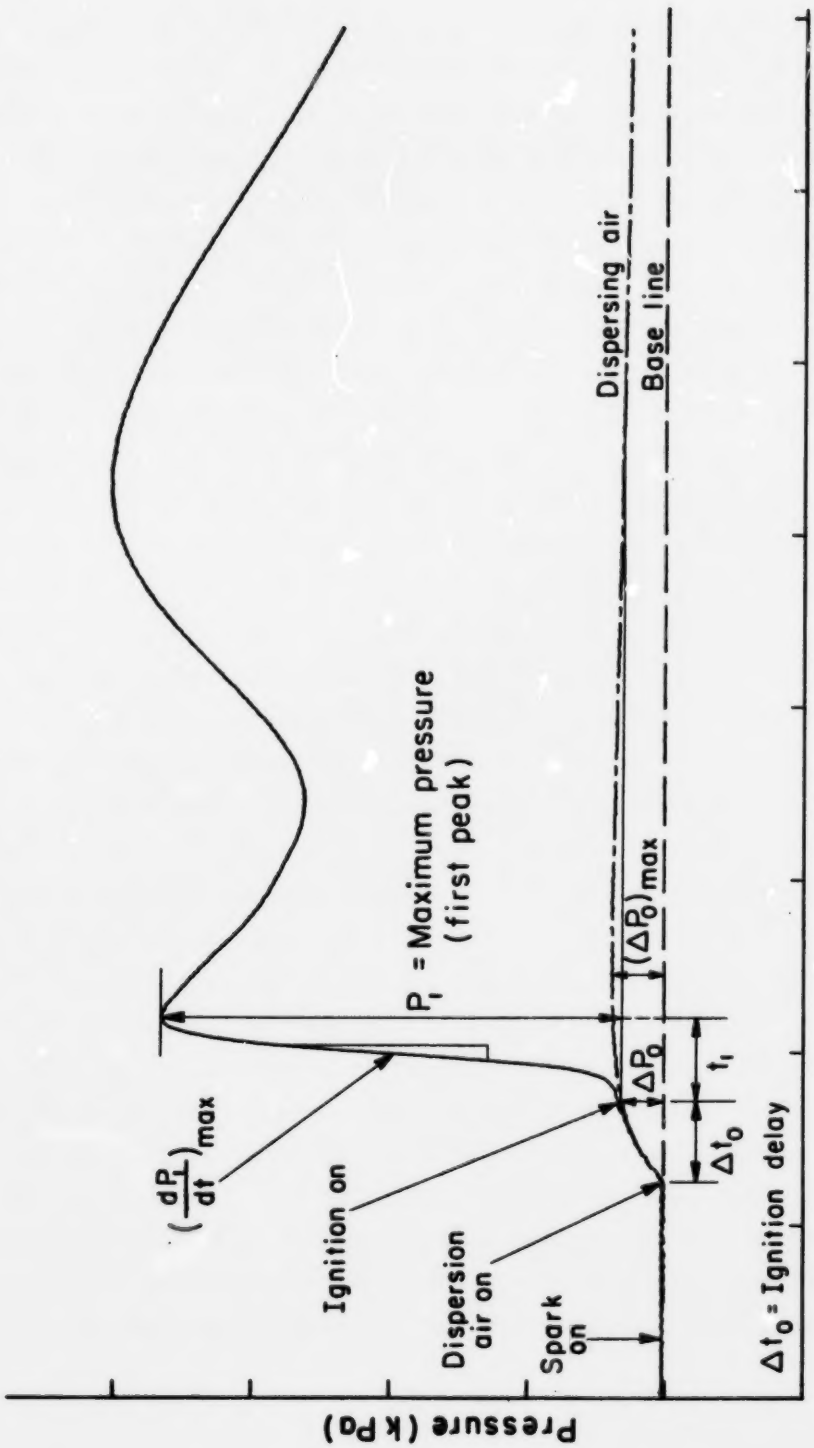

Fig. 3 - A pressure-time profile of dust explosion

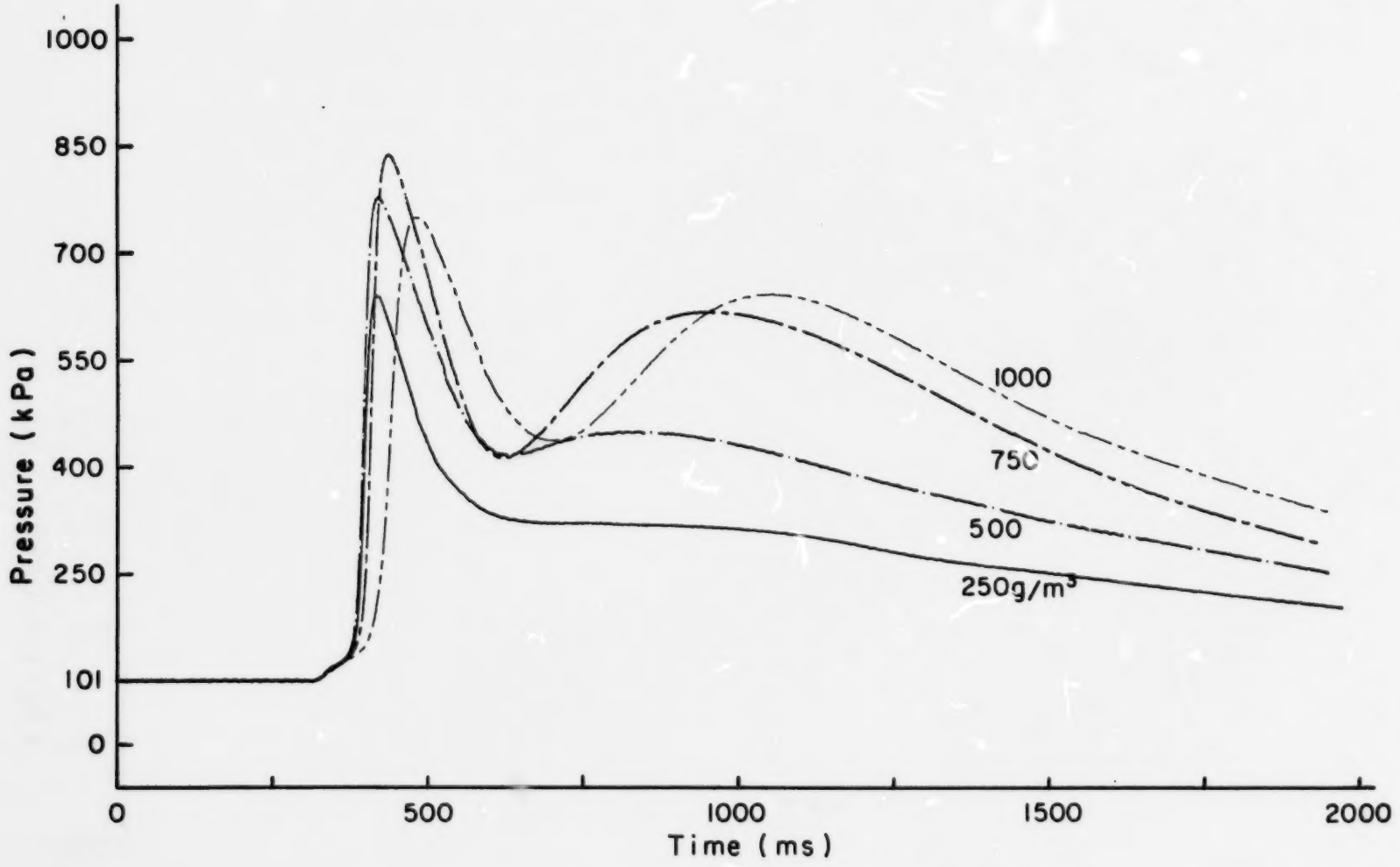

Fig. 4a - The dust explosion pressure-time profiles for -500 mesh ferrosilicon of 250 to 1000 g/m^3 samples

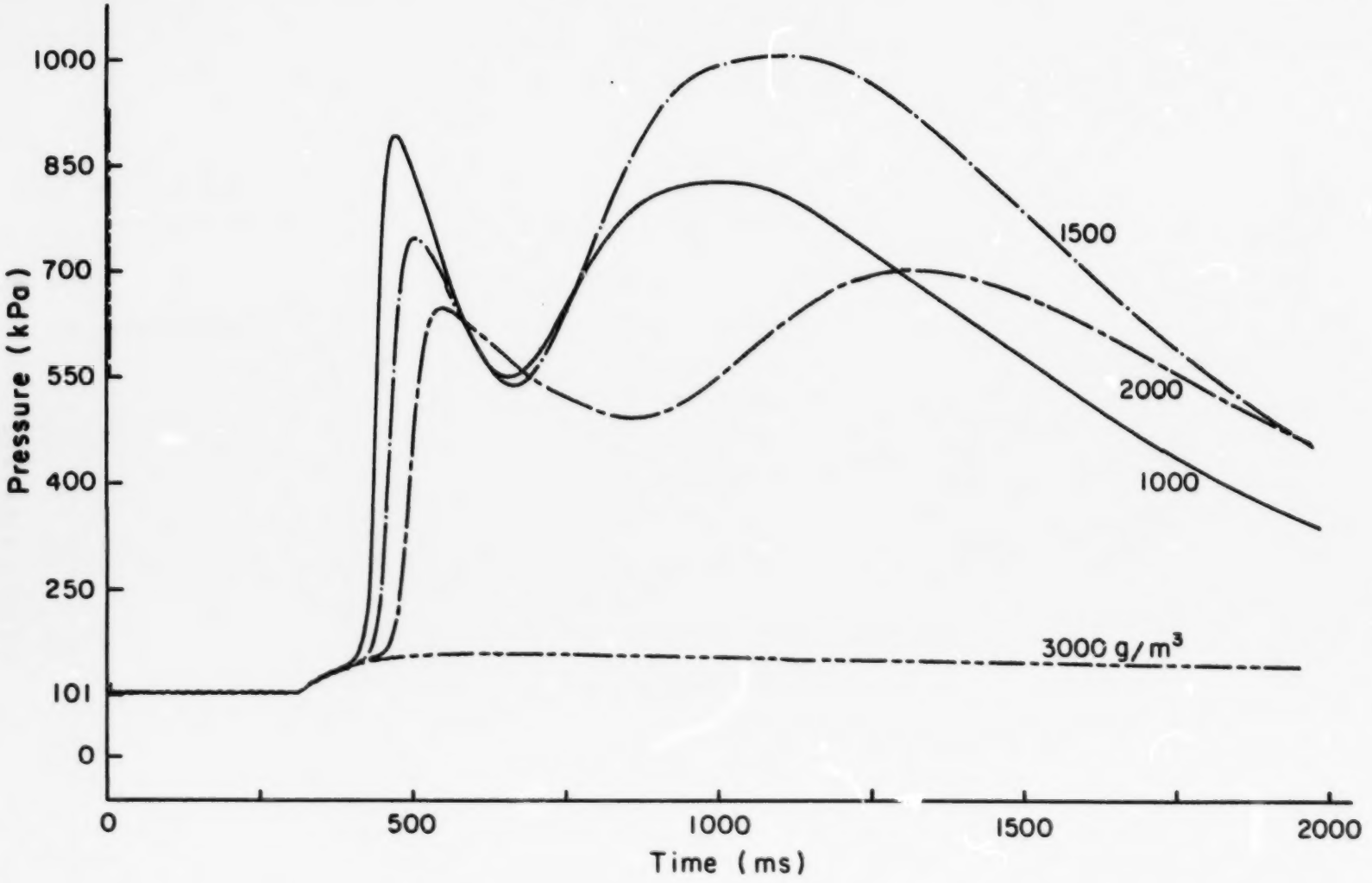

Fig. 4b - The dust explosion pressure-time profiles for -500 mesh ferrosilicon of 1000 to 3000 g/m^3 samples

Table 6 - Summary of ferrosilicon data in Tables 7 to 10 - comparison with data from reference (1)

Data source	Mesh size (-)	Particle size (μm)	Dust concentration (g/m³)	Average maximum pressure (kPa)	Average maximum rate of pressure rise (MPa/s)
CANMET	-20	-840	1000	400	3.4
77.7% Si	-200	-74	1000	320	2.1
			1500	342	3.0
83.0% Si	-325	-44	500	538	20.6
			750	586	19.0
			1000	600	14.4
			1500	516	8.8
			2000	430	3.4
	-500	-30	500	623	42.0
			750	655	36.8
			1000	686	34.2
			1500	649	19.8
			2000	504	9.3
ref (1)					
75.0% Si	-200	-74	500	579	18.3
			1000	620	24.1
			2000	648	17.9
82.5% Si	-200	-74	500	214	1.4
			1000	483	4.8
			2000	386	2.8

Table 7 - Summary of explosion tests for -20 mesh ferrosilicon

Dust concentration	Ignition delay	Maximum pressure P_1	Rates of pressure rise P_1/t_1	Rates of pressure rise $(dP_1/dt)_{max}$
g/m^3	ms	kPa	MPa/s	MPa/s
350	No ignition			
350	No ignition			
500	136	48	0.12	0.16
500	No ignition			
500	160	32	0.10	0.40
750	99	239	1.05	1.73
750	115	355	0.97	2.30
750	119	205	0.68	1.32
1000	99	463	1.87	3.94
1000	114	337	1.39	2.59
1000	92	472	2.05	4.69
1000	76	330	1.34	2.35
1500	166	130	0.48	0.69
1500	97	166	0.86	1.60
1500	98	224	0.64	0.81
2000	130	121	0.28	0.34
2000	128	198	0.74	1.42
3000	133	100	0.27	0.25
3000	No ignition			

Table 8 - Summary of explosion tests for -200 mesh ferrosilicon

Dust concentration	Ignition delay	Maximum pressure P_1	Rates of pressure rise P_1/t_1	Rates of pressure rise $(dP_1/dt)_{max}$
g/m^3	ms	kPa	MPa/s	MPa/s
250	No ignition			
300	No ignition			
500	80	210	0.70	1.21
500	93	154	0.42	0.71
500	100	170	0.39	0.78
750	112	327	1.40	2.71
750	111	334	0.98	1.94
750	113	348	1.43	2.82
1000	133	321	0.99	1.85
1000	150	342	0.93	1.84
1000	115	287	1.18	2.69
1000	109	337	1.10	2 28
1000	116	315	1.05	2.03
1500	129	379	1.68	3.87
1500	130	323	0.94	1.95
1500	114	325	1.45	3.06
2000	213	288	0.99	1.55
2000	195	94	0.24	0.43
3000	No ignition			
3000	200	36	0.09	0.20

Table 9a - Summary of explosion tests for -325 mesh ferrosilicon

Dust concentration	Ignition delay	Maximum pressure P_1	Rates of pressure rise P_1/t_1	Rates of pressure rise $(dP_1/dt)_{max}$
g/m^3	ms	kPa	MPa/s	MPa/s
150	No ignition			
200	No ignition			
200	63	353	3.03	6.85
250	64	437	4.85	11.9
250	47	460	4.85	15.1
250	49	470	5.00	15.5
250	64	409	2.87	6.8
500	66	541	6.93	23.6
500	61	540	7.95	25.4
500	63	504	5.87	16.3
500	65	562	6.77	18.3
500	67	545	6.00	19.6
750	84	544	5.55	16.1
750	82	646	7.34	22.9
750	83	600	6.72	18.3
750	84	524	5.51	16.2
750	81	564	6.41	18.9
750	68	585	4.38	13.3
750	62	643	8.57	27.6

Table 9b - Summary of explosion tests for -325 mesh ferrosilicon

Dust concentration	Ignition delay	Maximum pressure P_1	Rates of pressure rise P_1/t_1	$(dP_1/dt)_{max}$
g/m^3	ms	kPa	MPa/s	MPa/s
1000	86	527	4.74	15.0
1000	77	640	5.87	16.3
1000	97	557	4.89	14.5
1000	85	590	5.67	14.2
1000	81	576	4.06	11.4
1000	68	719	2.66	13.4
1000	99	590	4.83	15.9
1500	101	584	3.98	12.0
1500	98	539	3.88	11.3
1500	164	426	2.40	5.1
1500	131	514	2.71	6.7
2000	127	397	1.06	1.88
2000	131	421	1.87	4.37
2000	183	462	1.71	4.54
2000	166	440	1.40	2.97
3000	No ignition			
3000	183	251	0.73	1.14
3000	129	356	1.29	2.42

Table 10 - Summary of explosion tests for -500 mesh ferrosilicon

Dust concentration	Ignition delay	Maximum pressure P_1	Rates of pressure rise P_1/t_1	Rates of pressure rise $(dP_1/dt)_{max}$
g/m^3	ms	kPa	MPa/s	MPa/s
150	No ignition			
250	60	385	4.8	13.7
250	37	515	8.5	31.5
250	45	503	7.7	19.8
500	48	552	10.4	35.4
500	40	596	13.5	54.3
500	46	647	11.7	38.9
500	46	696	12.2	39.2
750	50	650	8.7	31.6
750	56	624	9.6	33.0
750	41	658	12.9	47.6
750	46	709	10.0	36.9
750	51	632	8.6	35.1
1000	62	667	9.0	31.7
1000	67	675	9.3	34.5
1000	50	685	10.2	42.5
1000	63	614	6.0	19.4
1000	49	729	8.7	35.5
1000	44	681	10.1	41.0
1000	65	754	8.0	34.9
1500	84	578	4.4	16.9
1500	78	760	6.3	23.4
1500	80	608	5.6	19.1
2000	97	507	2.6	6.4
2000	99	508	2.7	8.8
2000	113	497	4.0	12.8
3000	Two no ignition			
3000	312	88	0.4	0.59

Table 11a - Summary of explosion tests for lycopodium

Dust concentration	Ignition delay	Maximum pressure P_1	Rates of pressure rise P_1/t_1	$(dP_1/dt)_{max}$
g/m^3	ms	kPa	MPa/s	MPa/s
20	No ignition			
25	27	230	4.5	13.1
30	32	218	4.3	11.7
50	25	354	9.9	32.8
50	32	341	8.3	24.5
100	28	427	11.6	35.9
100	29	469	12.0	47.0
100	31	437	10.9	37.6
250	26	444	10.9	34.7
250	33	511	11.9	44.4
250	30	530	12.6	53.8
250	37	465	12.9	36.4
250	32	458	10.0	34.1
500	51	567	11.8	44.0
500	50	622	12.9	49.7
500	62	563	9.9	26.9
500	48	580	11.8	42.7
500	54	501	11.4	28.8
750	68	657	10.6	40.3
750	65	635	9.5	33.5
750	67	601	7.1	28.4
750	64	668	10.8	39.2

Table 11b - Summary of explosion tests for lycopodium

Dust concentration	Ignition delay	Maximum pressure P_1	Rates of pressure rise P_1/t_1	$(dP_1/dt)_{max}$
g/m^3	ms	kPa	MPa/s	MPa/s
750	65	598	7.7	36.3
750	47	664	8.8	40.2
750	63	552	10.4	36.7
750	64	640	11.4	28.6
1000	80	691	8.3	28.0
1000	78	723	11.5	38.5
1000	66	690	7.4	28.9
1000	75	710	8.5	28.6
1000	80	698	6.8	33.7
1000	67	729	9.5	42.2
1000	50	608	9.1	21.5
1500	133	592	6.1	13.8
1500	81	545	5.4	11.6
1500	114	630	4.3	11.4
1500	100	626	5.3	17.5
1500	47	612	6.0	14.6
1500	117	676	5.9	18.3
1500	83	639	5.4	24.7
2000	115	482	4.2	8.7
2000	180	594	4.4	13.8
3000	253	476	2.2	7.3

250, 500, 750, 1000, 1500, 2000 and 3000 g/m^3. Using the definitions and notations of Figure 3, the maximum explosion pressure, rates of pressure rise and ignition delay can be calculated from these pressure-time curves. Between two and seven tests were performed at each concentration. Analysis showed that an average of five tests at each concentration provides an approximate statistical result, and that an average of ten tests would be preferred if greater statistical precision were required in the circumstances.

The results of the analysis of the pressure traces are summarized in Tables 6 to 10 for the -20, -200, -325 and -500 mesh ferrosilicon samples. The -20 and -200 mesh results would have been more precise if more tests had been performed. Table 6 shows some of the data from Tables 7 to 10 along with comparable data from Reference (1).

Nearly all the tests for ferrosilicon, lycopodium and Pittsburgh coal produced double pressure peaks for this investigation. The second pressure peak has been shown to be a peculiar characteristic of the particular piezo-electric transducer employed. This second peak has subsequently been shown to be absent during dynamic calibration tests when two other transducer systems have been employed, i.e. another piezo-electric type and a strain-gauge type. Consequently, the second peak does not represent a real explosion phenomenon. Therefore, the maximum pressure and rates of pressure rise have been determined using the data applicable only to the first pressure peak. These first peak results of Tables 7 to 11 are used to produce the curves in Figs. 5 to 9.

For the size range of -20 to -500 mesh, the most explosive concentration of ferrrosilicon appears to be approximately 1000 g/m^3 with variations between 500 g/m^3 and 1500 g/m^3 for both maximum pressure and rate of pressure rise. The results indicate that the maximum pressure increases about twice for this size range whereas the maximum rate of pressure rise increases about ten-fold. This is a further indication that fine dusts burn much more rapidly than coarse dusts, as expected, and that the dust size has a greater effect on pressure rise rate than on maximum pressure attained.

These size range and within-range size distribution effects, coupled with the large changes associated with silicon content shown in Table 6, likely explain the difference between the results reported in (1) for which no size distribution is reported, and the CANMET results for otherwise corresponding samples.

Table 12 shows that the time duration of ignition delay increases with the increase of dust concentration and decreases with the reduction of particle size. This further indicates that fine particles and lean air-dust mixtures are easier to ignite than coarse particles and dense dust clouds. The ignition delays for the ferrosilicon dust clouds vary betweeen 40 and 300 ms approximately and between 30 and 250 ms for lycopodium powder.

The lycopodium is used as a reference material for the calibration of Hartmann apparatus. The test results are shown in Tables 11a, 11b, and Figures 9a and 9b for concentrations ranging from 25 to 3000 g/m³. The maximum explosion pressure, P_{max} = 693 kPa, occurred at a concentration of 1000 g/m³ and the average maximum rate of pressure rise, $(dP/dt)_{max}$ = 4C.7 MPa/s, occurred at a dust concentration of 250 g/m³. Table 13 compares these test results with those obtained by other laboratories in (5-7). The results are comparable and the agreement is reasonable considering there are some minor differences in test conditions with the air or arc delay and the dispersing air pressure.

SUMMARY

The minimum explosive concentration for the -37, -44, -74 and -840 µm ferrosilicon dusts is 165, 186, 284 and 318 g/m³, respectively. The fine ferrosilicon dusts are more sensitive to ignition and pose a greater explosion hazard than the coarse dusts because the smaller particles have more surface area per unit weight. The minimum explosive concentration for the reference materials, lycopodium and Pittsburgh coal, is 30 and 96 g/m³, respectively. The maximum explosion pressure for the -840, -74, -44 and -30 µm ferrosilicon is 400, 342, 600 and 686 kPa, and the maximum rate of pressure rise

for the same particle fractions is 3.4, 3.0, 20.6 and 42.0 MPa/s, respectively. The fine ferrosilicon dusts burn more violently than the coarse dusts.

The reduction of particle size has a greater influence on the rate of pressure rise producing a greater destructive force and a lesser effect on explosion pressure. The ignition delays for ferrosilicon dust clouds vary between 40 and 300 ms approximately, and for the lycopodium, between 30 and 250 ms. Fine particles and lean air-dust mixtures are more easily exploded than coarse particles and dense dust clouds.

Table 12 - Summary of ignition delays in milliseconds

Dust concentration g/m³	Ferrosilicon dust clouds				Lycopodium (±29 µm)
	-500 mesh	-325 mesh	-200 mesh	-20 mesh	
250	47	56	no ignition	no ignition	32
500	45	64	91	148	53
750	49	78	112	111	63
1000	57	85	125	95	71
1500	81	124	124	120	96
2000	103	152	204	129	148
3000	312	156	200	133	253

Table 13 - Literature comparison of lycopodium tests using 1.23 L Hartmann apparatus

Reference sources	Explosion pressure kPa	Rate of pressure rise MPa/s	Remarks
ASTM (4)	690 ± 83	43.4 ± 8.7	Recommended test at 750g/m^3.
This report	$\bar{X}$ = 627 S = 40.2	$\bar{X}$ = 35.4 S = 4.8	Tested at 750 g/m^3 with dust dispersing technique (B) and 100 ms air delay.
This report	P_{max}: $\bar{X}$ = 693 S = 40.3	$(dP/dt)_{max}$: $\bar{X}$ = 40.5 S = 7.1	P_{max} occurred at 1000g/m^3, $(dP/dt)_{max}$ occurred at between 100 and 250 g/m^3.
Enright (5)	P_{max}: $\bar{X}$ = 680 S = 20	$(dP/dt)_{max}$: $\bar{X}$ = 37.0 S = 2.0	P_{max} occurred at 1000 g/m^3 and $(dP/dt)_{max}$ occurred at 300 g/m^3 with dispersing air pressure of 500 kPa.
Jacobson (6)	P_{max}: X = 517	$(dP/dt)_{max}$: X = 21.4	P_{max} occurred at 500 g/m^3 and $(dp/dt)_{max}$ occurred at between 200 and 500 g/m^3 with dust dispersing technique (A) and air delay.
Field (7)	P_{max} X = 840	$(dP/dt)_{max}$ X = 76.3	P_{max} and $(dP/dt)_{max}$ are the highest maximum values obtained with 60 ms arc delay and dispersing air pressure of 830 kPa.

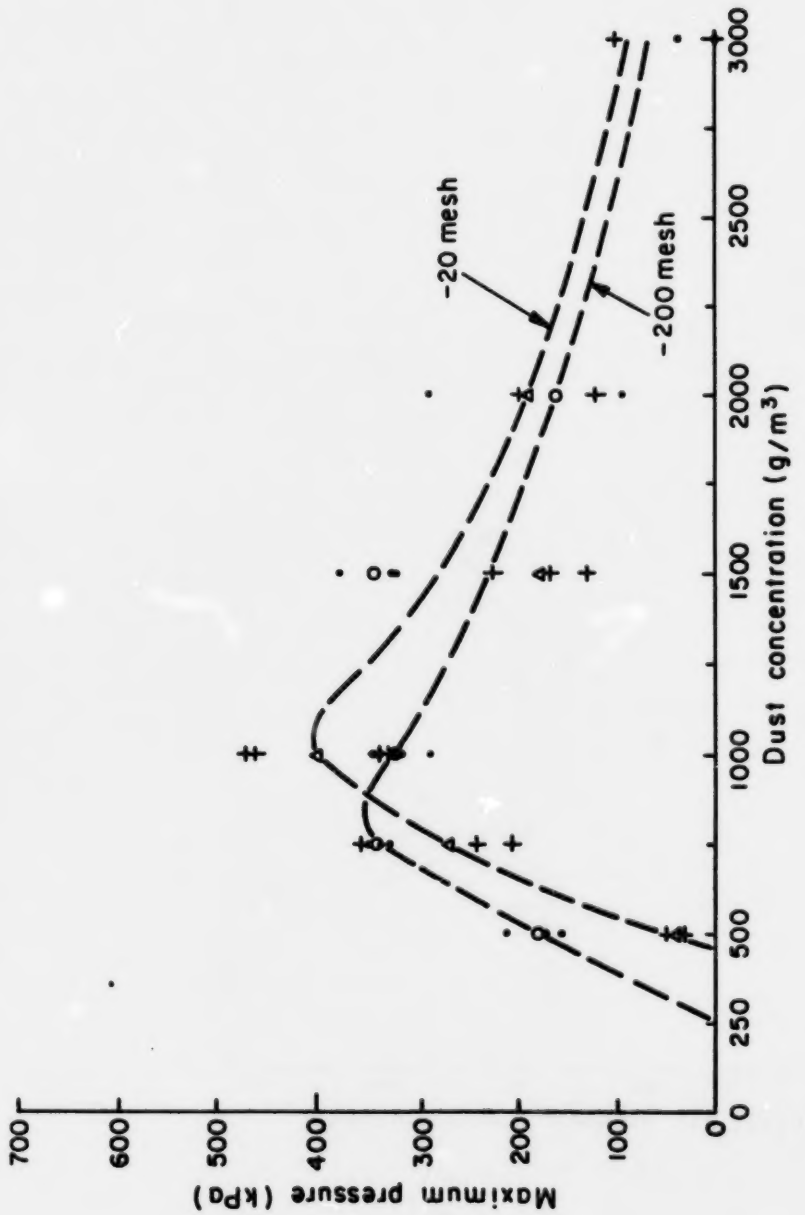

Fig. 5a - Maximum explosion pressure vs dust concentration for -20 mesh and -200 mesh ferrosilicon

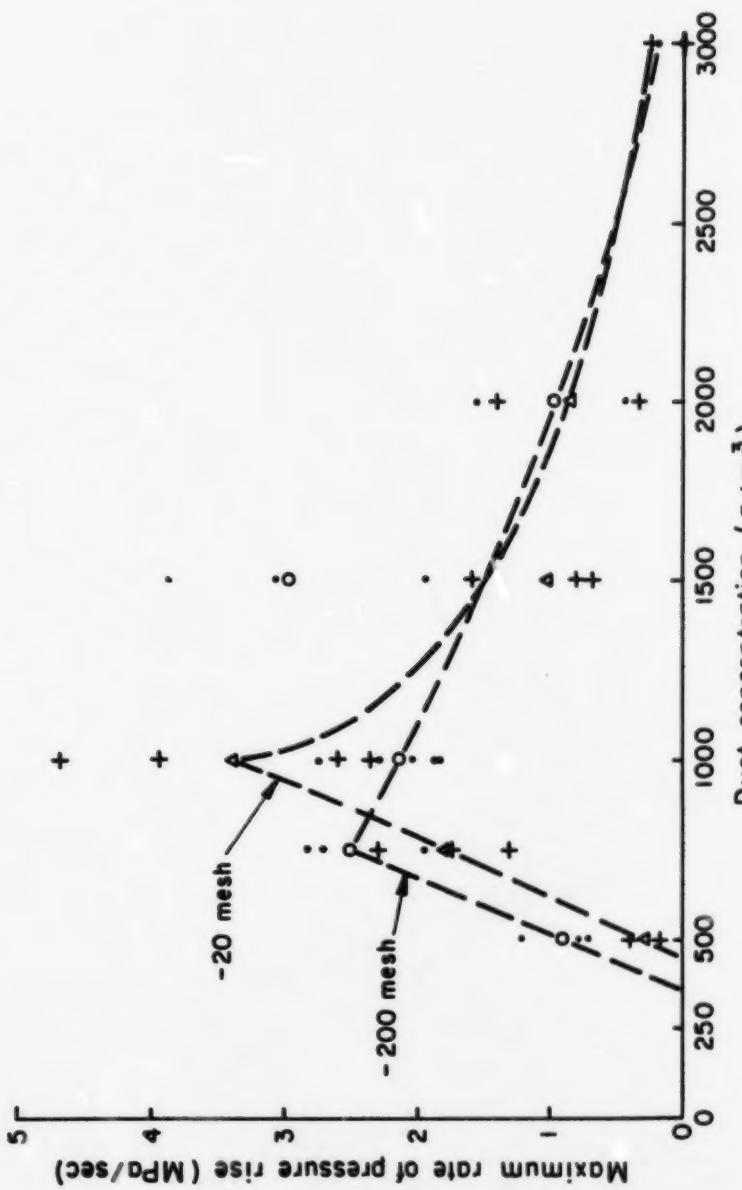

Fig. 5b - Maximum rate of pressure rise vs dust concentration for -20 mesh and -200 mesh ferrosilicon

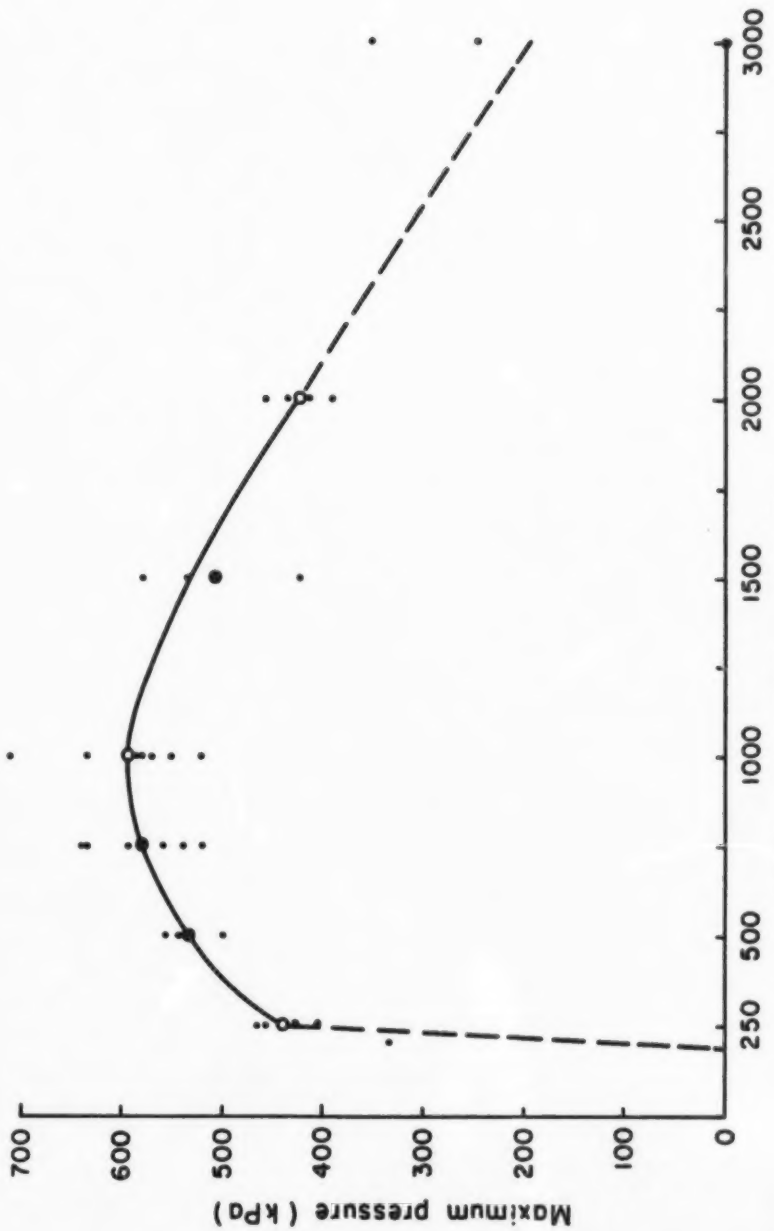

Fig. 6a - Maximum explosion pressure vs dust concentration for -325 mesh ferrosilicon

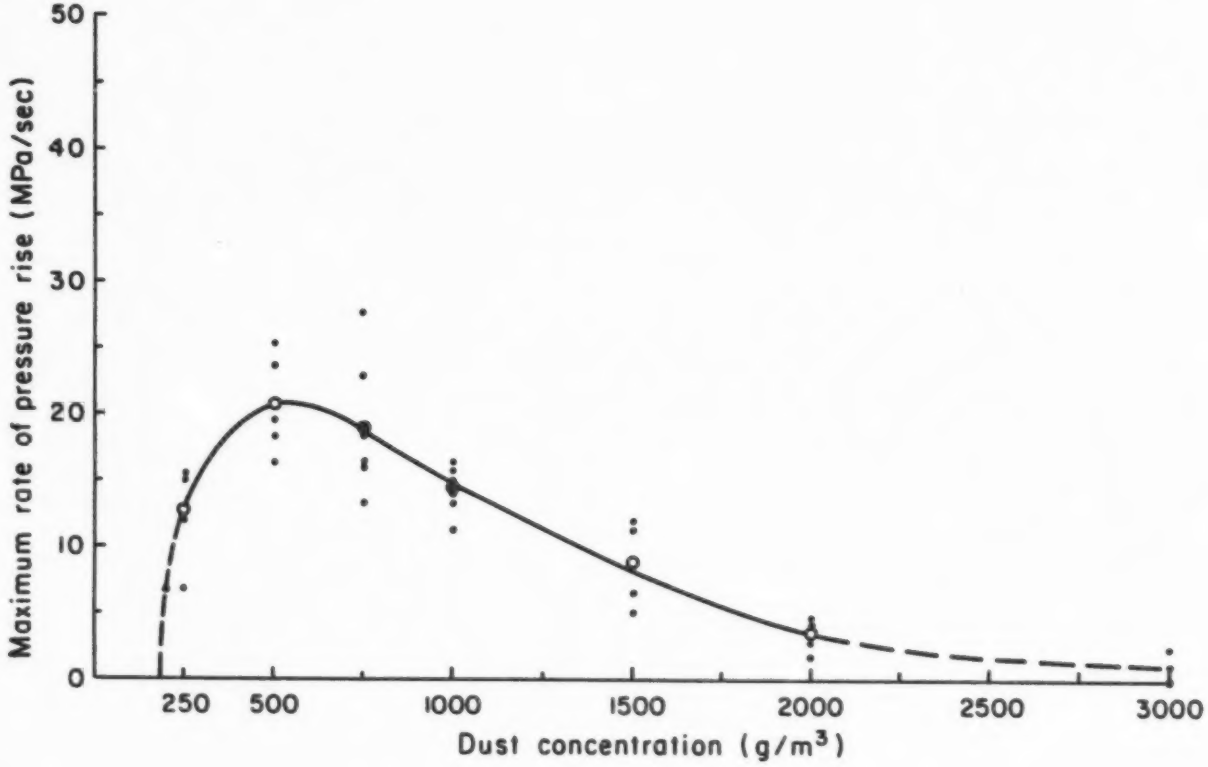

Fig. 6b - Maximum rate of pressure rise vs dust concentration for -325 mesh ferrosilicon

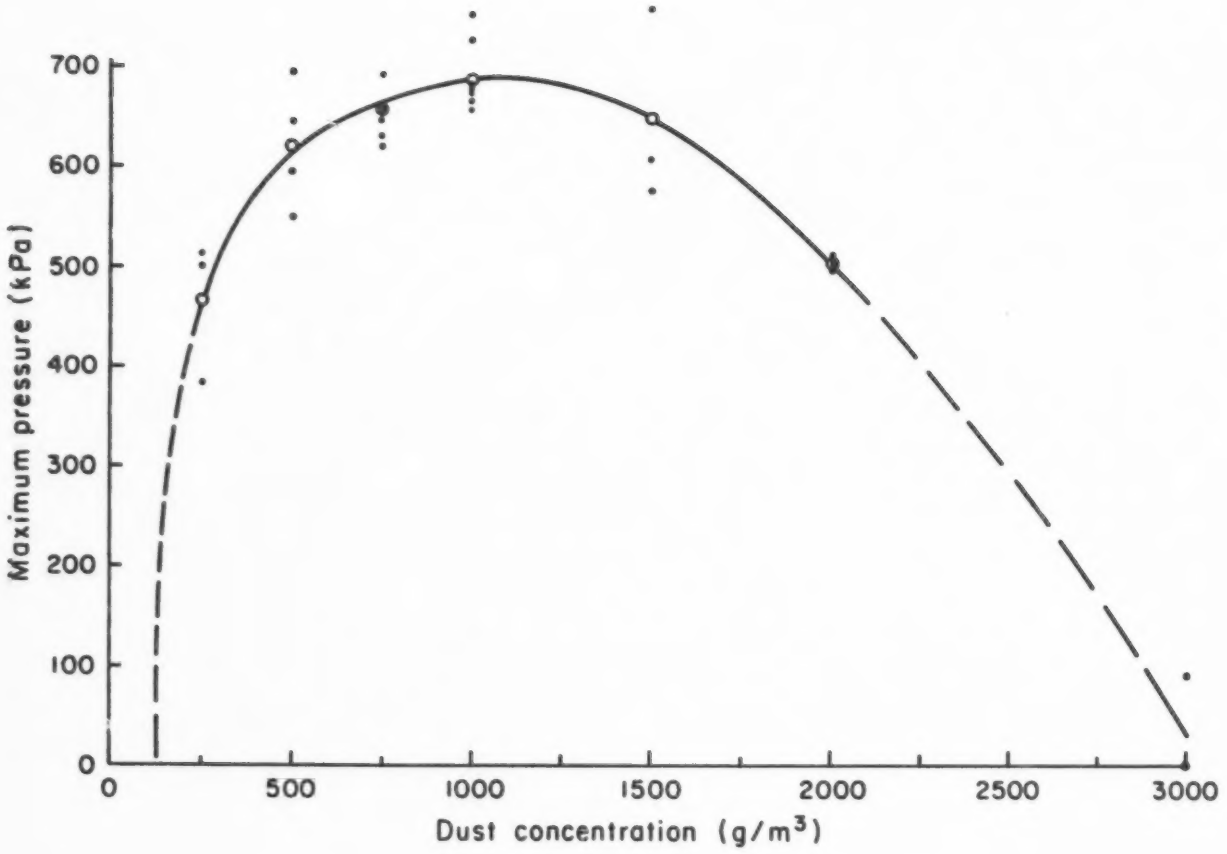

Fig. 7a - Maximum explosion pressure vs dust concentration for -500 mesh ferrosilicon

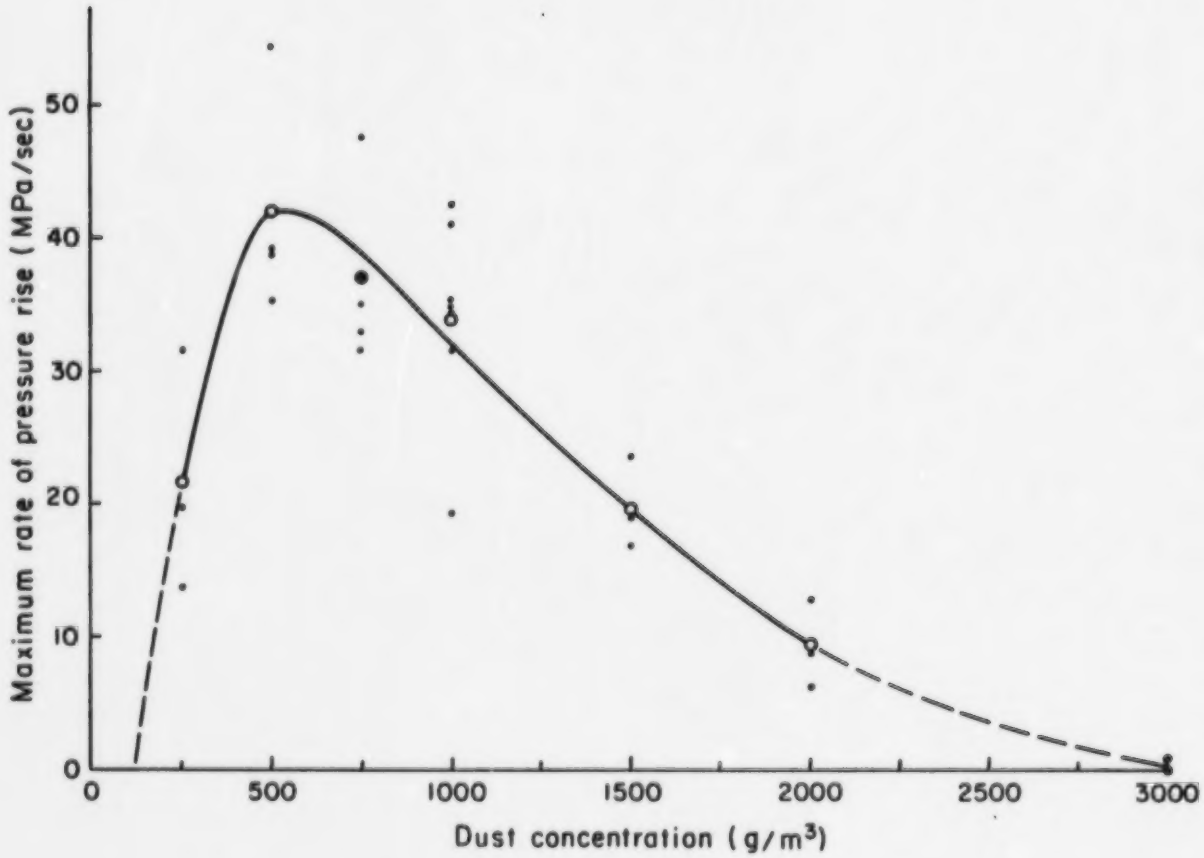

Fig. 7b - Maximum rate of pressure rise vs dust concentration for -500 mesh ferrosilicon

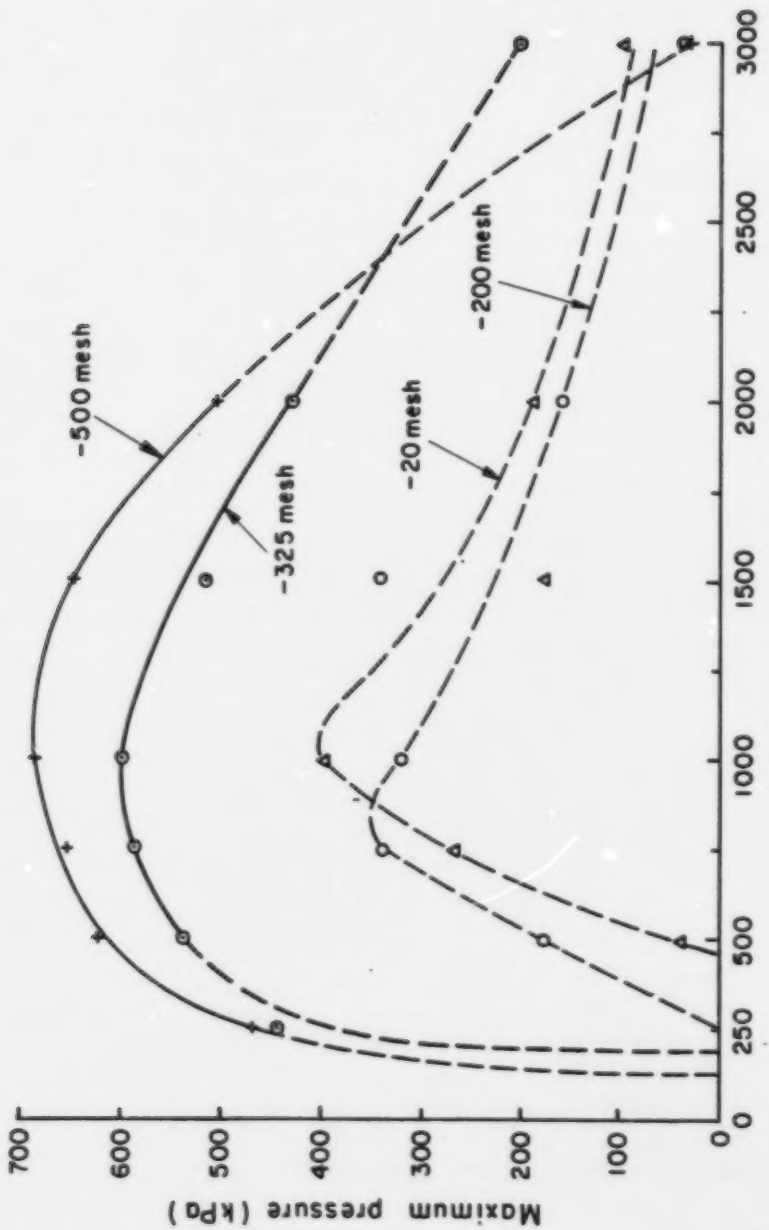

Fig. 8a - Maximum explosion pressure vs dust concentration for various sizes of ferrosilicon

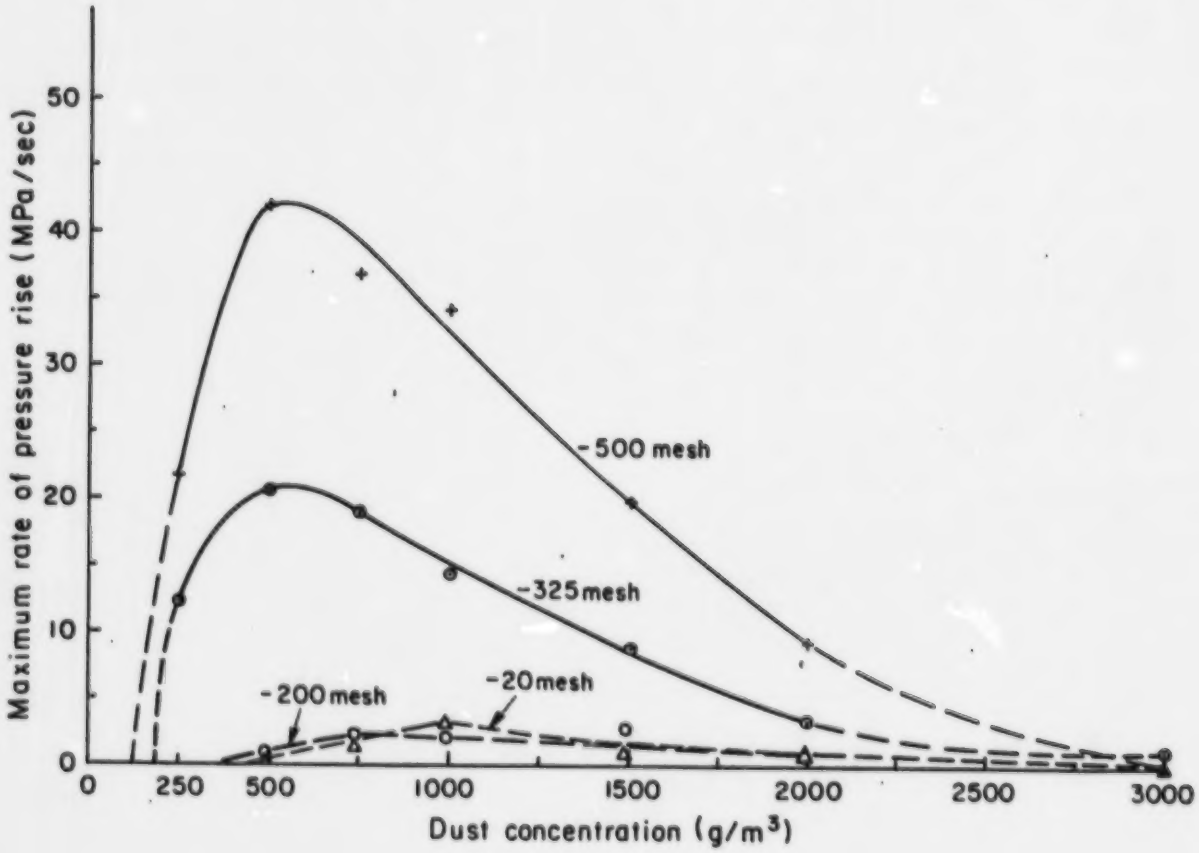

Fig. 8b - Maximum rate of pressure rise vs dust concentration for various sizes of ferrosilicon

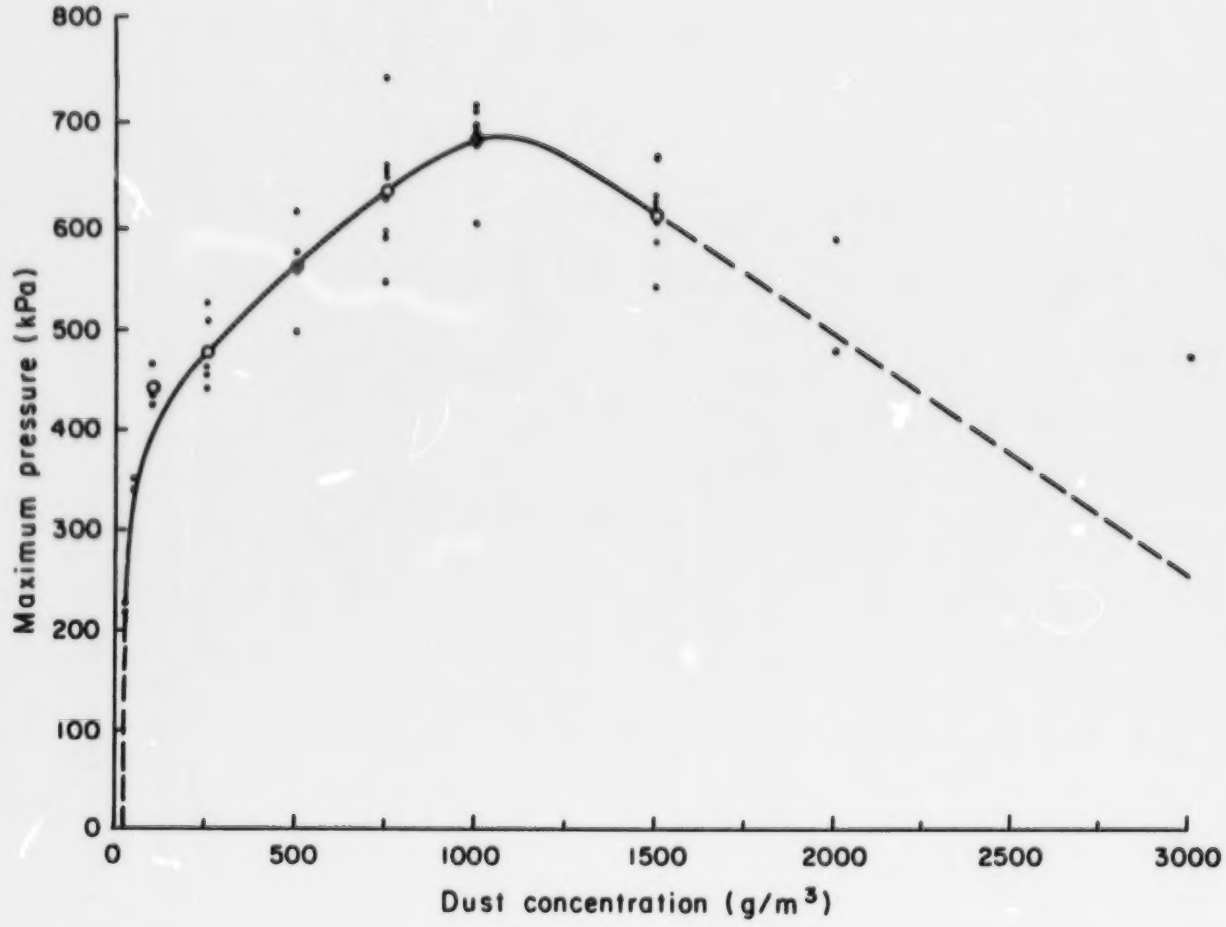

Fig. 9a - Maximum explosion pressure vs dust concentration for lycopodium powder

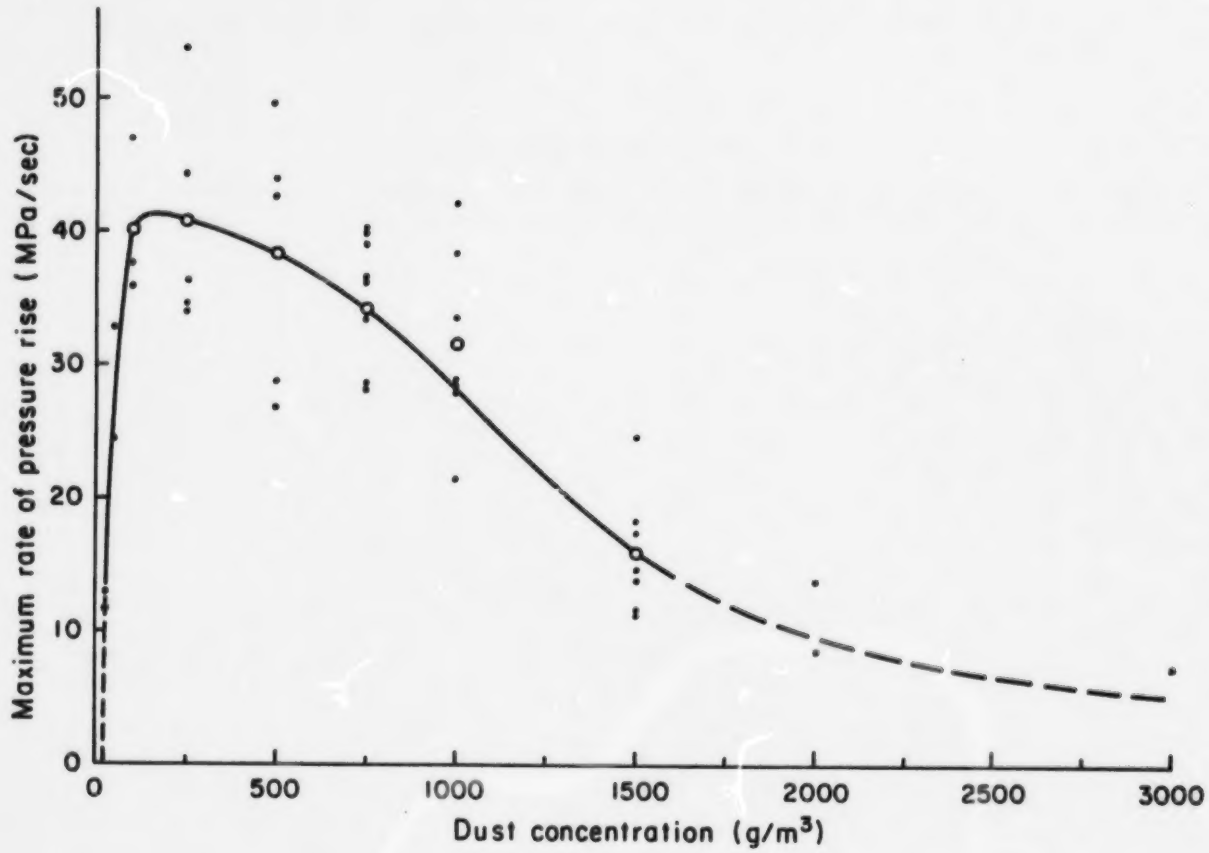

Fig. 9b - Maximum rate of pressure rise vs dust concentration for lycopodium powder

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APPENDIX A

EQUATIONS FOR THE CALCULATION OF EXPLOSIVE DUST CONCENTRATION

Mean of normalized weight, $\bar{y} = (\sum NiYi)/(\sum Ni) = A/N$ (1)

Variance of normalized weight, $S_y^2 = (B - A^2/N)/(N-1)$ (2)

Mean of log-normal distribution, $\bar{x} = \bar{y} \pm 0.5 \times d$ (3)

Std dev. of log-normal distribution, $S = 1.620 \times d\ (S_y^2/d^2 + 0.029)$ (4)

5% percentile variate, $X_{05} = \bar{X} - 1.645 \times S$ (5)

10% percentile variate, $X_{10} = \bar{X} - 1.282 \times S$ (6)

50% explosibility, $P_{50} = (\text{Antilog}\ (\bar{X})) + 1.23$ (7)

10% explosibility, $P_{10} = (\text{Antilog}\ (X_{10})) + 1.23$ (8)

5% explosibility, $P_{05} = (\text{Antilog}\ (X_{05})) + 1.23$ (9)

The above formulae are valid provided that the test result satisfies the following conditions in Eqs 10 and 11:

$$S_y^2/d^2 \geq 0.3 \quad (10)$$

$$0.5 \leq d/S \leq 2 \quad (11)$$

The units are: common log values in Eqs. 1 to 6, and g/m³ (nominal concentration) in Eqs. 7 to 9 for the 1.23 L combustion chamber.

APPENDIX B

CALCULATION OF 'UP-AND-DOWN' TEST RESULTS FROM DATA IN TABLE 3

$\bar{y} = 52.987 \div 21 = 2.5232$ (log)

$\bar{x} = 2.5232 + 0.5 \times 0.041 = 2.5437$ (log)

$$S_y^2 = \frac{[133.71182 - (52.987)^2 \div 21]}{(21 - 1)} = 7.765 \times 10^{-4}$$

$$S_y^2 / d^2 = \frac{7.765 \times 10^{-4}}{1.681 \times 10^{-3}} = 0.462 > 0.3$$

$S = 1.620 \times 0.041 \ (0.462 + 0.029) = 0.0326$ (log)

$d/S = 0.0410 \div 0.0326 = 1.26 \ (0.5 < 1.26 < 2)$

$x_{10} = 2.5437 - (1.282 \times 0.0326) = 2.502$ (log)

$x_{05} = 2.5437 - (1.645 \times 0.0326) = 2.490$ (log)

$P_{50} = (\text{Antilog } (2.5437)) \div 1.23 = 284.3 \text{ g/m}^3$

$P_{10} = (\text{Antilog } (2.502)) \div 1.23 = 258.3 \text{ g/m}^3$

$P_{05} = (\text{Antilog } (2.490)) \div 1.23 = 251.3 \text{ g/m}^3$